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13. SUPPLEMENTARY NOTES

14. ABSTRACT

One major accomplishment in this project was the development of the CLUSTer Error Reduction (CLUSTER) model's formalism. The updated equations can be downloaded at http://love.psy.utexas.edu/~love/cluster.pdf. One popular approach to modeling human category learning in the face of challenging data has been to propose models containing multiple systems. These system could include prototype, exemplar, or rule-based components, as well as gating mechanisms that determine how to combine the outputs from these systems or components. CLUSTER takes a complex systems approach in which "systems" emerge out of the learner's interactions with their environment. One claim is that what appears as separate cognitive systems are all based on cluster representations that follow from CLUSTER's recruitment and learning rules.

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Final Performance Report
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Bradley C. Love
1 University Station A8000
The University of Texas at Austin
Austin, TX 78712

brad_love@mail.utexas.edu
(tel) 512-232-5732
(fax) 512-471-5935

Review of Accomplishments and Findings

One major accomplishment in this project was the development of the CLUSTer Error Reduction (CLUSTER) model's formalism. The updated equations can be downloaded at http://love.psy.utexas.edu/~love/cluster.pdf. One popular approach to modeling human category learning in the face of challenging data has been to propose models containing multiple systems. These system could include prototype, exemplar, or rule-based components, as well as gating mechanisms that determine how to combine the outputs from these systems or components. CLUSTER takes a complex systems approach in which "systems" emerge out of the learner's interactions with their environment. One claim is that what appears as separate cognitive systems are all based on cluster representations that follow from CLUSTER's recruitment and learning rules.

CLUSTER has evolved a great deal over the project. Important changes include moving to Gaussian receptive fields, cluster-specific attention, and noise in the activation process. Gaussian receptive fields for clusters allow CLUSTER to show rule-like patterns of generalization (e.g., peak shift responding). Noise in the cluster activations serves many functions, including capturing data that indicate a shift to exemplar-based representations with extensive training. The noise in cluster activations makes cluster recruitment (in response to surprising stimuli) a stochastic process, meaning that eventually every exemplar is encoded by its own cluster with over training. Finally, allowing clusters to attend to whatever set of stimulus properties reduces responding error allows CLUSTER to scale up to learning situations in which multiple domains (e.g., natural kinds and artifacts) are simultaneously acquired, as well as allows CLUSTER to capture recognition memory findings from behavioral studies conducted in the laboratory.

One recognition finding that has been correctly predicted by CLUSTER is that the recognition memory for oddball items (e.g., an exception to a rule) is driven by having to differentiate the oddball item from similar items that that contrast with the oddball item (e.g., are in a different category). This prediction differs from the most popular account (since Von Restorff) of oddball memory enhancement which holds that oddball items are remembered better because they are relatively isolated in stimulus space. Recent work in the lab has demonstrated that isolation effects in category learning are attributable to the lack of properly matched foils and that differentiation drives the creation of high-fidelity memory traces:

Sakamoto, Y., & Love, B. C. (2006). Vancouver, Toronto, Montreal, Austin: Enhanced oddball memory through differentiation, not isolation. *Psychonomic Bulletin & Review*, 13, 474-479.

This work follows from behavioral and simulation work published in December of 2004 on a similar topic:

Sakamoto, Y., & Love, B. C. (2004) Schematic Influences on Category Learning and Recognition Memory. *Journal of Experimental Psychology: General*, 133, 534-553.

Modeling-wise, we continue to look ahead to extending CLUSTER so that it can be applied to reinforcement learning situations. CLUSTER is a clustering model of human category learning that is being developed under this grant. While working on deriving candidate learning rules for CLUSTER, Matt Jones and the PI realized that CLUSTER could be extended using the Q-Learning method to be a model of reinforcement learning with category learning simply being a special case in which environmental feedback is only relevant to evaluating the previous action.

This insight could potentially be very important. CLUSTER is designed to uncover the natural goal-relevant chunks (i.e., clusters) of a learner's environment, mirroring the structures discovered by human learners. These clusters may provide an effective, low-dimensional representation that can speed reinforcement learning. CLUSTER extended to reinforcement learning would allow it to be applied to virtually any problem (e.g., learning to control an aircraft). Matt Jones and the PI believe the model could be extended to provide a dynamical system/connectionist rival to production systems like John R. Anderson's ACT-R architecture. The lab is excited about the prospect of integrating category learning with reinforcement learning and addressing learning and performance problems that Air Force personnel face on a daily basis.

Although the CLUSTER work was the main focus of this funded effort, many related projects have also bore fruit. One project has successfully related CLUSTER's mechanisms to a learning circuit involving prefrontal cortex and structures in the medial temporal lobe:

Love, B. C., & Gureckis, T. M. (2007). Models in search of a brain. *Cognitive, Affective, & Behavioral Neuroscience*, 90-108.

Gureckis, T. M., & Love, B. C. (2006). Bridging levels: Using a cognitive model to connect brain and behavior in category learning. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Work led by Matt Jones has explored how recently experienced stimuli exert an influence on classification behavior. This line of work separates the contributions of short- and long-term influences on classification behavior. In terms of short-term influences, the use of probabilistic category structures allowed for independent estimates of perceptual and decisional recency effects:

Jones, M., Love, B. C., & Maddox, W. T. (2006) Recency as a window to generalization: Separating decisional and perceptual sequential effects in category learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*, 316-332.

Jones, M., Maddox, W. T., & Love, B. C. (2006). The role of similarity in generalization. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Jones, M., Maddox, W. T., & Love, B. C. (2005). Stimulus generalization in category learning. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

One extension of the work with CLUSTER was to consider how people learn categories or patterns that are defined over relations and features. The vast majority of research in human learning focuses on categories defined solely by features. Many real world concepts are relational in nature. For example, a "predator" is defined in relation to "prey", not by some set of perceptual features. As another example, visual scenes are often understood in terms of the spatial relations among objects. In this line of work, a cognitive model is developed that bridges work in analogy and category learning. The model, Building Relations through Instance Driven Gradient Error Shifting (BRIDGES), extends ALCOVE, an exemplar-based connectionist model of human category learning (Kruschke, 1992). Unlike ALCOVE which is limited to featural or spatial representations, BRIDGES can appreciate analogical relationships between stimuli and stored predicate representations of exemplars. Like ALCOVE, BRIDGES learns to shift attention over the course of learning to reduce error and, in the process, alters its notion of similarity. A shift toward relational sources of similarity allows BRIDGES to display what appears to be an understanding of abstract domains, when in fact performance is driven by similarity-based structural alignment (i.e., analogy) to stored exemplars. Simulations of animal, infant, and adult support BRIDGES. Current work considers how to extend BRIDGES's exemplar-based representations to more general cluster-based representations as used in the CLUSTER model (but with relational content). Other efforts involve empirical tests with human subjects:

Tomlinson, M., & Love, B. C. (2006). From pigeons to humans: Grounding relational learning in concrete examples. *Twenty-First National Conference on Artificial Intelligence* (AAAI-2006), *USA*, *21*, 136-141.

Tomlinson, M., & Love, B. C. (2006). Learning abstract relations through analogy to concrete exemplars. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Tomlinson, M., & Love, B. C. (2007). Relation-Based Categories are Easier to Learn than Feature-Based Categories. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Other work involving relational processing demonstrates that people perceive objects that play the same relational role (a baseball bat and a golf club are both used for *hitting*) as being more similar. A computational model that extends existing corpora approaches to automatically extracting meaning from text is developed that incorporates lessons from these empirical studies:

Jones, M., & Love, B. C. (2007). Beyond common features: The role of roles in determining similarity. *Cognitive Psychology*, 55, 196-231.

Jones, M., & Love, B. C. (2004). Beyond common features: The role of roles in determining similarity. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Research Personnel:

Bradley C. Love, Principal Investigator.

Tyler Davis, Ph.D. student, third year. Two publications under review.

Todd M. Gureckis, Ph.D. student, Todd is now an assistant professor at NYU.

Mathew Jones, postdoctoral researcher (was supported by an NRSA fellowship). Matt Jones is now an assistant professor at Colorado.

Levi B. Larkey, Ph.D. student, After completing his degree, Levi did a postdoc at Los Alamos National Laboratory.

Yasuaki Sakamoto, Ph.D. student, Yasu is now a research assistant professor as Stevens Institute of Technology.

Marc Tomlinson, Ph.D. student, fourth year. Two publications under review.

Publications:

Peer Reviewed Articles

Gureckis, T. M., & Love, B. C. (invited, special issue). Short Term Gains, Long Term Pains: Reinforcement Learning in Dynamic Environments. *Cognition*.

Gureckis, T. M., & Love, B. C. (invited, special issue). Solving Partially Observable Markov Decision Processes via Reinforcement Learning. *Journal of Mathematical Psychology*.

Love, B. C., & Gureckis, T. M. (2007). Models in search of a brain. *Cognitive, Affective, & Behavioral Neuroscience*, 90-108.

Jones, M., & Love, B. C. (2007). Beyond common features: The role of roles in determining similarity. *Cognitive Psychology*, 55, 196-231.

Sakamoto, Y., & Love, B. C. (2006). Vancouver, Toronto, Montreal, Austin: Enhanced oddball memory through differentiation, not isolation. *Psychonomic Bulletin & Review*, 13, 474-479.

Jones, M., Love, B. C., & Maddox, W. T. (2006) Recency as a window to generalization: Separating decisional and perceptual sequential effects in category learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*, 316-332.

Love, B. C. (2005). Environment and goals jointly direct category acquisition. *Current Directions in Psychological Science*, *14*, 195-199.

Sakamoto, Y., & Love, B. C. (2004). Schematic influences on category learning and recognition memory. *Journal of Experimental Psychology: General*, *133*, 534-553.

Love, B. C., Medin, D. L., & Gureckis, T. M. (2004). SUSTAIN: A network model of category learning. *Psychological Review*, *111*, 309-332.

Gureckis, T. M., & Love, B. C. (2004). Common mechanisms in infant and adult category learning. *Infancy*, *5*, 173-198.

Peer Reviewed Proceedings

Gureckis, T. M., & Love, B. C. (2007). Behaviorism Reborn? Statistical Learning as Simple Conditioning. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Davis, T., Love, B. C., & Maddox, W. T. (2007). Translating From Perceptual to Cognitive Coding. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Tomlinson, M., & Love, B. C. (2007). Relation-Based Categories are Easier to Learn than Feature-Based Categories. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Rein, J. R., Love, B. C., & Markman, A. B. (2007). Feature Relations and Feature Salience in Natural Categories. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Gureckis, T. M., & Love, B. C. (2006). Bridging levels: Using a cognitive model to connect brain and behavior in category learning. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Love, B. C., & Jones, M. (2006). The emergence of multiple learning systems. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Sakamoto, Y., & Love, B. C. (2006). Sizable sharks swim swiftly: Learning correlations through inference in a classroom setting. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Sakamoto, Y., Love, B. C., & Jones, M. (2006). Tracking variability in learning: Contrasting statistical and similarity-based accounts. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Jones, M., Maddox, W. T., & Love, B. C. (2006). The role of similarity in generalization. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Tomlinson, M., & Love, B. C. (2006). Learning abstract relations through analogy to concrete exemplars. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Tomlinson, M., & Love, B. C. (2006). From pigeons to humans: Grounding relational learning in concrete examples. *Twenty-First National Conference on Artificial Intelligence* (AAAI-2006), *USA*, *21*, 136-141.

Gureckis, T. M., & Love, B. C. (2005). A critical look at the mechanisms underlying implicit sequence learning. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Jones, M., Maddox, W. T., & Love, B. C. (2005). Stimulus generalization in category learning. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Sakamoto, Y., & Love, B. C. (2005). A novel approach to understanding novelty effects in memory. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Jones, M., & Love, B. C. (2004). Beyond common features: The role of roles in determining similarity. *Proceedings of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum Associates.

Sakamoto, Y., & Love, B. C. (2004). Type/token information in category learning and recognition. *Proceedings of the Cognitive Science Society.* Mahwah, NJ: Lawrence Erlbaum Associates.

Love, B. C., & Gureckis, T. M. (2004). The hippocampus: Where a cognitive model meets cognitive neuroscience. *Proceedings of the Cognitive Science Society.* Mahwah, NJ: Lawrence Erlbaum Associates.

Sakamoto, Y., Matuska, T., & Love, B. C. (2004). Dimension-wide vs. exemplar-specific attention in category learning and recognition. In M. Lovett, C. Schunn,

C. Lebiere, and P. Munro (Eds.), *Proceedings of the International Conference of Cognitive Modeling* (pp. 261-266). Mahwah, New Jersey: Lawrence Erlbaum.

Publications - Other

Love, B. C. (2005). Method and apparatus for incorporating decision making into classifiers. US Patent #6,920,439.

Love, B. C., & Tomlinson, M. (invited chapter). Rule-based vs. similarity-based concept learning. In Denis Mareschal, Paul Quinn, Stephen Lea (Eds.), *The Emergence of Uniquely Human Concepts?*

Love, B. C., & Gureckis, T. M. (invited chapter). Varieties of Sequential Learning. In B. H Ross (Ed.), *The Psychology of Learning and Motivation.*

Love, B. C. (2005). In vivo or in vitro: Cognitive architectures and task specific models. In R. W. Pew and K. A. Gluck, *Modeling Human Behavior with Integrated Cognitive Architectures: Comparison, Evaluation, and Validation.* 351-364. Mahwah, NJ: Lawrence Erlbaum.

Love, B. C., & Gureckis, T. M. (2005). Modeling learning under the influence of culture. In W. Ahn, R. L., Goldstone, B. C., Love, A. B., Markman, & P. Wolff (Eds.), *Categorization inside and outside of the lab: Festschrift in Honor of Douglas L. Medin.* 229-248. Washington, DC: American Psychological Association.

Ahn, W., Goldstone, R. L., Love, B. C., Markman, A. B., & Wolff, P. (Eds.). (2005). *Categorization inside and outside of the lab: Festschrift in Honor of Douglas L. Medin.* Washington, DC: American Psychological Association.

Presentations:

In addition to the conference papers listed above and presentations at the Annual Meeting of the Psychonomic Society, the PI has given the invited talks listed below.

9/2007	"Human Inference Mechanisms," Cowles Foundation for Research in Economics, Yale University, workshop on "Analogies, Rules, and Probabilities."
3/2007	"Learning by Example with Extension to Dynamic Environments," AFOSR Cognition & Decision Program Workshop, Dayton, OH.

2/2007	"The Emergence of Multiple Learning Systems," University of Arizona.
2/2007	"Putting the Psychology Back Into Psychological Models," AFOSR sponsored workshop in Dynamic Decision Making, Dayton, OH.
11/2006	"The Emergence of Multiple Learning Systems," University of Louisiana.
7/2006	"The Emergence of Multiple Learning Systems," ICOM, Sydney, Australia.
7/2006 Australia.	"Models in Search of a Brain," workshop, Margaret River,
6/2006 Australia.	"The Emergence of Multiple Learning Systems," UWA,
4/2006	"The Emergence of Multiple Learning Systems," AFOSR Cognition & Decision Program Workshop, Dayton, OH.
4/2006	"The Emergence of Multiple Learning Systems," APA Convention Invited Division 3 speaker, New Orleans, LA.
10/2005	Speaker/Symposium Organizer, "The Cognitive Neuroscience of Category Learning," at the Computational Cognitive Neuroscience Conference, Washington, D.C.
9/2005	"Acquiring Knowledge One Cluster at a Time," Department of Psychology, New York University, NYC.
7/2005	"Exemplar-based relational category learning," Annual Summer Interdisciplinary Conference (ASIC) 2005, Briançon, France.
6/2005	Workshop Participant, NSF sponsored "Dynamical and Connectionist Accounts of Development," University of Iowa, organized by John Spencer and Jay McClelland.
5/2005	"A Clustering Account of Human Categorization," Department of Psychology, University of Sydney, Australia.

4/2005	"Cluster-based Modeling of Human Learning: Joint Influences of Task and Environment," AFOSR Perception & Cognition Program Workshop, St. Augustine, FL.
4/2005	"Environment and goals jointly direct category acquisition," Department of Psychology, Texas A&M, College Station, TX.
2/2005	Keynote speaker for Lake Ontario Visionary Establishment Conference.
2/2005	"Beyond common features: The role of roles in determining similarity. " Department of Psychology, The University of Western Ontario.
1/2005	"Clustering Account of Human Learning" Department of Psychology, Stanford University.
1/2005	"Clustering Account of Human Learning" Department of Psychology, UCSD.
10/2004	"Bridging Levels: A Cognitive Model of Hippocampal Mediated Learning," J. S. McDonnell Foundation meeting on the cognitive neuroscience of category learning, New York City, NY.
9/2004	"Bridging Levels: A Cognitive Model of Hippocampal Mediated Learning" Department of Communication Sciences and Disorders, The University of Texas at Austin.